The Surface-Tension Method of Visually Inspecting Honeycomb-Core Sandwich Plates

By SAMUEL KATZOFF

National Aeronautics & Space Adm.
Langley Field, Virginia

SUMMARY

When one face of a metal-honeycomb-core sandwich plate is heated or cooled relative to the other, heat transfer through the core causes the temperature on each face at the lines of contact with the core to be slightly different from that on the rest of the face. If a thin liquid film is applied to the face, the variation of surface tension with temperature causes the liquid to move from warmer to cooler areas and thus to develop a pattern corresponding to the temperature pattern on the face. Irregularities in the pattern identify the locations where the core is not adequately bonded to the face sheet. The pattern is easily observed when a fluorescent liquid is used and illumination is by means of ultraviolet light. Observation in ordinary light is also possible when a very deeply colored liquid is used. A method based on the use of a thermographic phosphor to observe the temperature pattern was found to be less sensitive than the surface-tension method. A sublimation method was found to be not only less sensitive but also far more troublesome.

INTRODUCTION

Considerable interest exists at present in honeycomb-core sandwich construction for the skin of high-speed aircraft. In the typical construction of such a skin a metal honeycomb core is brazed or welded to two thin metal face sheets. Inspecting such a sandwich after it has been fabricated—in particular, determining whether the honeycomb core is actually bonded to the two face sheets at every point along all the presumed contact lines—would seem to pose a formidable problem.

The main purpose of the present note is to describe a simple visual inspection method—the surface-tension method—that has recently attracted some interest for this application. The method is based on heat transfer from one face to the other through the honeycomb core by way of the contact lines. Methods depending on heat transfer do not, of course, indicate directly the mechanical strength of the bond, except for the plausible assumption that good thermal contact implies good bonding.

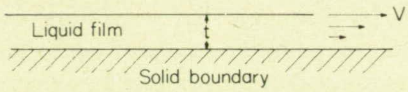
Some other possible visual methods depending on heat transfer through the core will also be briefly mentioned. In general, however, the surface-tension method appears to be the simplest and most sensitive of all such methods.

BASIS OF METHOD

Origin and Effect of Surface-Tension Gradients

The surface tension of most liquids decreases with increase in temperature. The rate of decrease is generally very small—on the order of 0.1 dyne/cm/°C. Nevertheless, when a surface that is wet with a thin liquid film acquires temperature nonuniformities of a few degrees, the resulting surface-tension gradients drag the liquid from the warmer to the cooler areas so that large variations in film thickness quickly result.

Consider a liquid of viscosity μ in a thin film of thickness t as in the following sketch:



Let the surface-tension gradient along the free surface of the liquid film be $d\gamma/dx$ (where γ is surface tension and x is distance along the surface) and let the resulting velocity at the free boundary be V. The relationships must be such that the surface-tension force at the free boundary balances the viscous force at the solid boundary, or

$$\frac{d\gamma}{dx} = \mu\frac{V}{t}$$

As an example, let $t = 0.01$ centimeter, $\mu = 0.01$ poise, and $\frac{d\gamma}{dx} = 0.2$ dyne/cm/cm (corresponding to a temperature gradient of about 1° C in 0.5 centimeter). Then,

$$V = \frac{t}{\mu}\frac{d\gamma}{dx} = 0.2 \text{ cm/sec}$$

The motion would be set up almost instantly, since the inertia of the thin film is negligible.

Thus, it is apparent that even small temperature gradients result in flows that, within seconds, can markedly change the distribution of liquid over the solid surface. The motion presumably slows down when the film thickness t in the warmer areas becomes so small that V must become correspondingly small for $\mu V/t$ to remain equal to $d\gamma/dx$.

The only definite mention of the effect in the literature seems to be that given in reference 1, which clearly described it, correlated it with some common observations, and outlined a small mathematical analysis of the equilibrium condition.

Application

Basically, the technique of application consists of spreading a thin film of liquid over one face of the metal sandwich plate and applying heat to the opposite face. The liquid should thin out along lines of contact between the core and the face sheet where the bonding has been successful, and it should fail to thin out where the bonding has not been successful. Figure 1 indicates schematically what should be expected at good and bad contacts.

Applying cold instead of heat should result in an opposite pattern, in which the liquid shows peaks instead of valleys where the bonding is good. Applying heat by radiation directly to the face that has the liquid film should yield a similar result, since the honeycomb will conduct heat away from the face wherever the bonding is good. Cooling the opposite face in this last case should help. All three techniques have been used successfully.

A basic question in the application of the method is the choice of

Reprinted from The March-April, 1960 issue of "Nondestructive Testing"

PRINTED IN U.S.A.

liquid. It should have low viscosity, should not be too volatile, should wet metals easily, should have adequate variation of surface tension with temperature, and should be easily observable visually in very thin films.

The first three requirements are easily satisfied by suitably chosen members of many families of organic compounds—hydrocarbons, alcohols, esters, halides, and so on. The fourth requirement (adequate variation of surface tension with temperature) is also satisfied by most organic liquids; and while some, as the straight-chain saturated hydrocarbons, show somewhat more variation than others, this requirement seems on the whole not to be particularly restrictive. The last requirement—visibility in very thin films, presents the only material problem. Different approaches to the problem of visibility have been tried. These are outlined in the following sections.

FLUORESCENT LIQUIDS

Formulation

An elegant solution to the problem of visibility is to use a fluorescent liquid and observe it in a dark room under ultraviolet light (3660 A). The basic advantages in the use of fluorescent liquids for such purposes are (1) the film appears to glow with its own radiance so that observations are not disturbed by extraneous reflections or high lights, and (2) in principle, even the thinnest films can be made visible by sufficiently intense ultraviolet illumination, in contrast with a thin film of, say, a colored liquid, the perception of which is not improved by increasing the intensity of white-light illumination. Films can be obtained that are clearly visible in even a low-power ultraviolet beam and that show clear patterns. A too strong concentration of some fluorescent materials is to be avoided, since the thinned-out film in the valleys may then show less contrast with the thicker liquid film.

Two different types of fluorescent kerosene solutions were used and found satisfactory. These were (1) A half-saturated solution of an oil-soluble fluorescent dye in kerosene. The dye was obtained from Wilmot and Cassidy, Inc., 108-112 Provost Street, Brooklyn 22, N. Y., and is designated as Fluorescent Green C.H. 185% dye. A similar dye is available from Ultra-Violet Products, Inc., 5114 Walnut Grove Avenue, San Gabriel, Calif., and is designated as Blak-Ray Fluorescent Oil additive No. DF-502. (2) Any heavy petroleum-base lubricating oil diluted with about four parts of kerosene. All such oils are fluorescent. A gear oil (Navy symbol gear oil No. 6135) was used in the author's studies, mainly because it was at hand and was known to be strongly fluorescent.

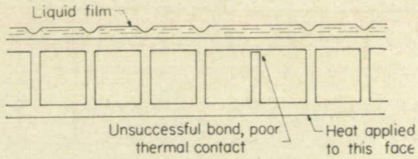


Figure 1—Sketch showing the working of the surface-tension method.

Solution (1) seemed generally somewhat the better of the two.

In photographing the patterns obtained with fluorescent liquids the use of a filter in front of the camera lens is necessary to remove the ultraviolet light. A Wratten 2A or 2B filter, for example, will filter out the ultraviolet light and transmit most of the visible fluorescence. It may also be worth mentioning that, for long periods of working under ultraviolet light, some similar yellow-glass protection for the eyes is equally desirable.

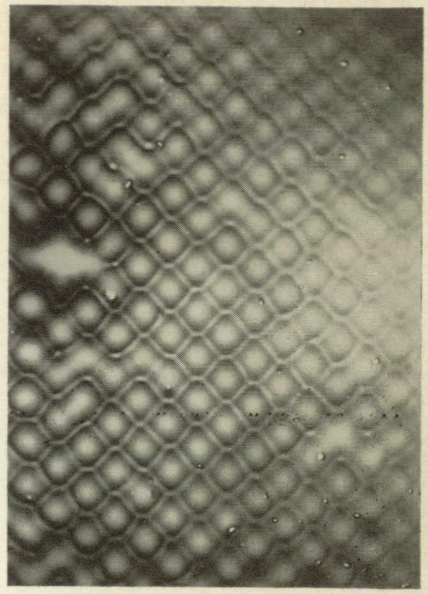


Figure 3—Reversed honeycomb pattern that develops, with use of certain liquids, subsequent to the initial pattern. Area shown is same as that shown in right-hand photograph of Figure 2 and was obtained with the same fluorescent liquid.

Results with Fluorescent Liquid on a Titanium Sandwich Plate

The honeycomb patterns shown in Figure 2 were developed by use of a fluorescent dye solution on a 5/8-inch-thick titanium sandwich plate with 0.022-inch-thick face sheets. A pair of opposite faces of the same sample

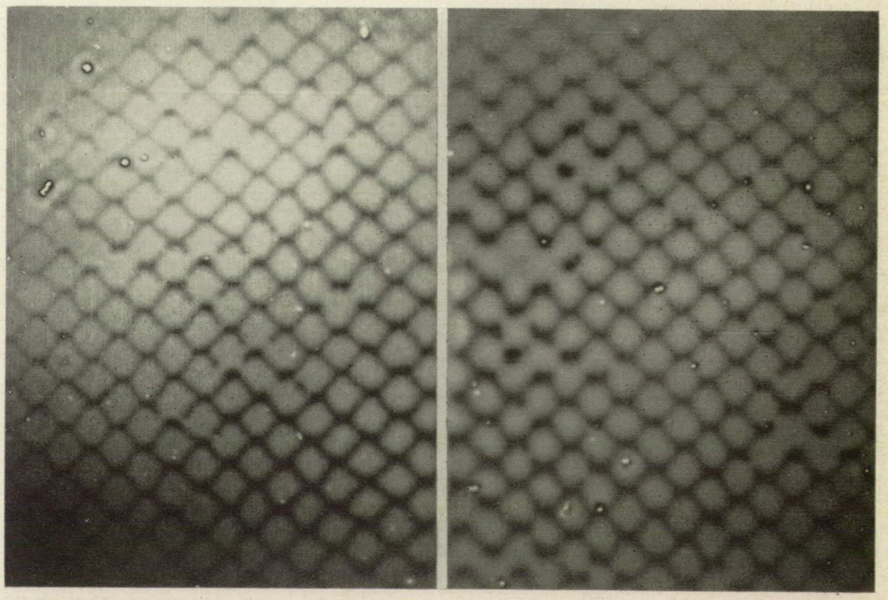


Figure 2—Honeycomb patterns developed on a titanium sandwich plate by use of the surface-tension method with a fluorescent liquid. Both faces of the sandwich plate are shown juxtaposed so that, if defects were carried through from one face to the other, the two patterns would be mirror images of each other.

are shown juxtaposed so that, if defects were carried through from one face to the other, the two patterns would be mirror images of each other. The defective areas appear different on the two faces, presumably because of lateral heat flow within the honeycomb. Thus, visual observation of one face cannot, in general, detect defects at the opposite face.

The technique used in obtaining these patterns was quite unrefined. The solution was flowed over the surface and then allowed to drain off by holding the surface vertical. The sandwich plate, with the wet face up, was then held over an electric hotplate for about 5 seconds. The pattern was fully developed after a few more seconds. It is not necessary to continue the heating after the pattern begins to appear.

The pattern eventually fades as the heat becomes distributed over the face sheet. Before it fades, however, an interesting reversal of the pattern occurs in which the lines appear bright and sharply outlined instead of dark and somewhat diffuse (Fig. 3). The reason for the reversal is not known but at present it is believed to be related to the fact that the solvent is not a pure compound but contains a range of hydrocarbons. Possibly, the evaporation of the lighter constituents at the warm bond lines changes the proportions (particularly since the fluid is thinned out at these lines) in such a way that the surface-tension gradient is reversed. A possible confirmation of this theory is the fact that three fluorescent liquids made by dissolving the fluorescent dye in pure compounds (butyl salicylate, butyl oleate, and n-hexadecane) did not show the reverse pattern. Also, butyl salicylate alone, which is itself fluorescent (although not very bright in comparison with the solutions), did not show the reverse pattern. It may still be possible, however, that a solution of the dye in some pure liquid could show the reverse pattern if evaporation of the solvent at the bond lines results in a sufficient increase of local dye concentration to increase the local surface tension. In the present studies, reversal of the pattern did not occur until after the basic pattern (such as in Figure 1) had been fully developed. Since the effect may tend to confuse in certain cases, however, use of a pure compound as solvent may be generally best.

The bright dots visible in the photographs have no significance. They are merely bits of dust that fell on the surface during the test.

The titanium sandwich plate was eventually split through the honeycomb core with a bandsaw so that the bonding with the face sheets could be observed directly and correlated with the indications of the fluorescent liquids. It was found that, where a line (that is, a boundary between two adjacent cells) or part of a line was clearly missing from the photographs of Figure 2, the contact was generally sufficiently open so that, with carefully directed illumination and observation, light could be seen through it. Even where the defect was barely detectable on the photograph, a trace of light could generally be seen through it. With special care in observation, it was also possible to see a few tiny openings, some much smaller than 0.01 inch, where the photograph did not indicate a defect.

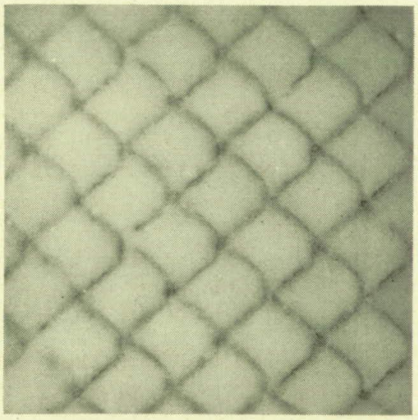


Figure 4—Fluorescent oil pattern on a stainless steel sandwich plate. Courtesy of The Martin Co.

A sensitive method of determining, in the split plate, whether a bond is not quite tight is to drop some liquid (such as a light solvent) into the cell and observe whether it runs through the bond to the adjacent cell. Using the fluorescent liquid for this purpose and observing under ultraviolet light makes this technique extremely sensitive. In general, the results of this test correlated with the defects indicated in the photographs and with the tiny openings discovered visually.

On the whole then, it appeared, with this plate at least, that the fluorescent liquids adequately located the defects. Whether an unbonded joint might still be in such firm contact as to permit good heat transfer (and hence a deceptive pattern) could not be determined, since no such firm but unbonded joints were found. It should be pointed out, however, that other studies (for example, ref. 2) have indicated that firm contact alone provides much less heat transfer than a metal bond.

Results with Fluorescent Liquids on Stainless-Steel Sandwich Plates

In addition to the titanium sandwich plate shown in Figure 2, three stainless-steel sandwich plates were tested by this method. Two of these presented rather unfavorable conditions because of their particularly heavy face sheets. They required several times as much heat as did the other two plates, and even then the patterns were not very sharp. When the heat was applied more rapidly, however, with the fully open burner of a gas stove, quite adequate patterns were developed. The heated faces in these tests became too hot to touch, although not nearly hot enough to endanger the bonding. No defects were apparent in the patterns. The only observable irregularities were a few spots on one of the plates where the liquid consistently thinned out especially rapidly. The extra heat transfer at these points probably indicates some local excesses of bonding metal.

This particular plate had been considered somewhat questionable because the bonds that could be seen around the edge of the plate showed almost no fillets, in contrast with other comparably fabricated plates. Accordingly, as a further check, the plate was split through the honeycomb core in order to permit direct observation of the bonding. No defective bonds could be found.

Figure 4, obtained by Mr. G. V. Thompson, then with The Martin Co.,

is a striking example of the technique, showing remarkable detail in the bonds. Mr. H. Parent of The Martin Co. has also sent me recently a fluorescent oil pattern of the face of a metal honeycomb plate, together with an x-ray shadowgram of the same plate. The brazing compound cast strong shadows in the shadowgram where it accumulated at the good bonds, but it failed to cast a shadow where the oil pattern showed a bad bond. The two pictures thus correlated exellently.

Results with Fluorescent Liquids on Adhesive-Bonded Aluminum Alloy Honeycomb Sandwich Plates

In addition to the preceding all-metal sandwich plates, three aluminum alloy sandwich plates were available in which the bonding was effected by means of organic adhesives. Such adhesives, of course, are much poorer heat conductors than are metal bonding alloys. Nevertheless, the fluorescent liquid was able to show the patterns on all three plates, although the patterns were not nearly as sharp as those seen on the all-metal plates. The patterns also showed all sorts of irregularities of sharpness and intensity which, however, could not be interpreted as defects. For example, on one of the plates the visible pattern appeared as a patchwork of very narrow strips and lines of different intensities. These strips and lines, like brush-marks, probably reflect the irregularities in thickness that resulted when the adhesive was brushed manually over the face sheet. The bond lines on the patterns also tended to be spotty in appearance. All these peculiarities no doubt result from the poor heat conductivity of the adhesive, which causes small variations in local adhesive thickness to result in large variations in local heat transfer. The plate with the thickest face sheet showed the least irregularity. The reason is probably not that the bonding was more uniform but that lateral heat conduction in the face sheet tends to reduce the sharpness of lateral temperature gradients in a thick face sheet as compared with the gradients in a thin face sheet.

One of these plates was of particular interest since the bonding along a 1-inch-wide strip of one face sheet had been purposely made "defective"; in particular, one of the steps in the application of the adhesive had been omitted along this strip, so that the total amount of the adhesive on this strip was much less than that over the remainder of the face sheet. The fluorescent-oil pattern, however, quite failed to show this "defective" band; and when the plate was eventually split to permit direct observation, the bonds within this band appeared tight. Data on whether the modified bonding technique actually results in a mechanically inferior product are not available.

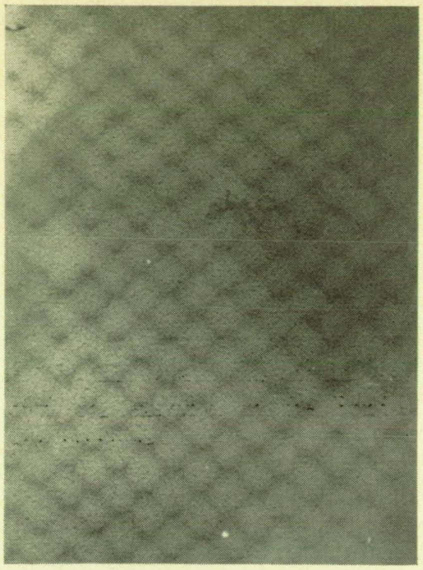


Figure 5—Honeycomb pattern obtained by use of the sublimation method with naphthalene. Area shown is same as that shown in right-hand photograph of Figure 2.

COLORED LIQUIDS

Instead of a fluorescent liquid, a deeply colored liquid may be used, with observation under ordinary white light. To improve contrast, observation may be under light of the complementary color (or, what is the same thing, under white light with the observer looking through a filter of the complementary color). Such a deeply colored liquid is the Bondcheck fluid developed by the Magnaflux Corporation and included in their Bondcheck kit. Many striking and clearly visible patterns have been obtained with this liquid, as shown, for example, in the Bondcheck brochure.

It may be of interest to add a few words regarding the technique of heating the model. Although any of the previously mentioned heating techniques can be used, the suggested technique for use with Bondcheck is to heat the wet face by radiation. The bond locations in this case are then cooler than the rest of the face so that much of the liquid is drawn to these locations. As a result of this accumulation of liquid, the bond locations stand out as dark lines, although the film over the face may have been initially so thin that its color was quite weak. If the heating technique were to consist of heating the opposite face, the bond lines would then be warm, and the liquid at the bond lines would thin out; the contrast with the weak color over the rest of the face might then be relatively poorer. If the liquid film were originally applied to the face somewhat more thickly for this case, however, its color would be stronger and hence so also would be the contrast. Thus, in general, a reasonable insight into the phenomenon shows how to adjust the details of the technique according to the problem.

OTHER METHODS BASED ON HEAT TRANSFER

Thermographic-Phosphor Method

The United States Radium Corporation, Morristown, New Jersey, produces a fluorescent temperature-sensitive pigment, that is, a pigment whose fluorescence under ultraviolet light is strongly dependent on temperature. The material may be applied to a surface in the form of a suspension in a lacquer type of vehicle; however, it is also being produced, in essentially this form, as decal sheets for easier application. When a sample of the decal was attached to one face of the sandwich plate of Figure 2 and the other face was strongly heated for a few seconds, the pattern of bond lines and defects became visible under ultraviolet light, although the amount of detail and the degree of contrast were considerably less than could be seen with the surface-tension method.

The pattern did not show a subsequent reversal. This fact is con-

sidered as additional evidence that the reversal observed with some liquids does not reflect a reversal of the temperature gradients.

Sublimation Method

If one face of the sandwich plate is covered with a thin coat of a white volatile powder and the face is then heated, say, by radiation while the opposite face is kept cool, a pattern should develop because of the different rates of sublimation. That is, the powder will sublime away slowly along the cool bond lines and will sublime away more rapidly in the areas between the bond lines and at the faulty bond lines. Eventually, bare metal will be exposed between the lines, while the lines themselves will still be white. The method is somewhat related to the well-known sublimation method of flow visualization. A number of volatile solids useful in this method are listed in Reference 3.

In the present tests naphthalene (moth balls) was used as the volatile solid. A solution in a light solvent was sprayed on the face in such a way that the spray particles were practically dry when they hit the surface. Subsequent heating under an inverted hotplate while the opposite face rested in a freezing mixture at –20° F developed the pattern shown in Figure 5. The freezing mixture was not necessary but was used in this case to improve the pattern for purposes of photography. In other tests ice water was found to be adequate.

Such photographs are, in fact, somewhat difficult to obtain. Since, generally, neither the film thickness nor the heating is uniform, the pattern develops at different rates over different areas of the plate. Accordingly, a photograph taken at any particular time may show considerable nonuniformity of contrast, with some areas perhaps completely clear while other areas are just beginning to show the pattern. Under a continuous observation, however, the defects all become identifiable at one time or another during the course of the test.

Since the method seems troublesome, time-consuming, and relatively insensitive, compared with the surface-tension method, it will not be further discussed.

REFERENCES

(1) Hershey, Allen V.: Ridges in a Liquid Surface Due to the Temperature Dependence of Surface Tension. *Phys. Rev.* (Letters to the Editor). Vol. 56, No. 2, Second Ser., July 15, 1939, p. 204..

(2) Barzelay, Martin E., Tong, Kin Nee, and Holloway, George F.: Thermal Conductance of Contacts in Aircraft Joints. National Advisory Com-Committee for Aeronautics Technical Note 3167, 1954.

(3) Main-Smith, J. D.: Chemical Solids as Diffusible Coating Films for Visual Indications of Boundary-Layer Transition in Air and Water. Reports and Memoranda No. 2755, British Aeronautical Research Council, 1950.